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SEAS AT THE MILLENNIUM: AN ENVIRONMENTAL EVALUATION

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Chapter 23

THE GULF OF ALASKA

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The Gulf of Alaska (GOA) is a large (336,000 km^2) and productive ecosystem, but is showing increasing signs of being influenced by global-scale events, including global warming and contamination. The natural beauty of the rugged coastline, the vast wilderness, and the pristine waters still represent an ecosystem that is clean and pure. Government agencies, both State of Alaska and federal, have been mostly successful in managing the GOA's resources. These organizations are attempting to apply an ecosystem management approach to protecting and utilizing the resources found in this northern ecosystem. However, ecosystem management requires a baseline of understanding of the natural history of the species that ply these waters, and little information exists. Research associated with the *Exxon Valdez* oil spill, and with the University of Alaska and resource management agencies has advanced the understanding of this region tremendously, but much more needs to be done.

Seas at The Millennium: An Environmental Evaluation (Edited by C. Sheppard)

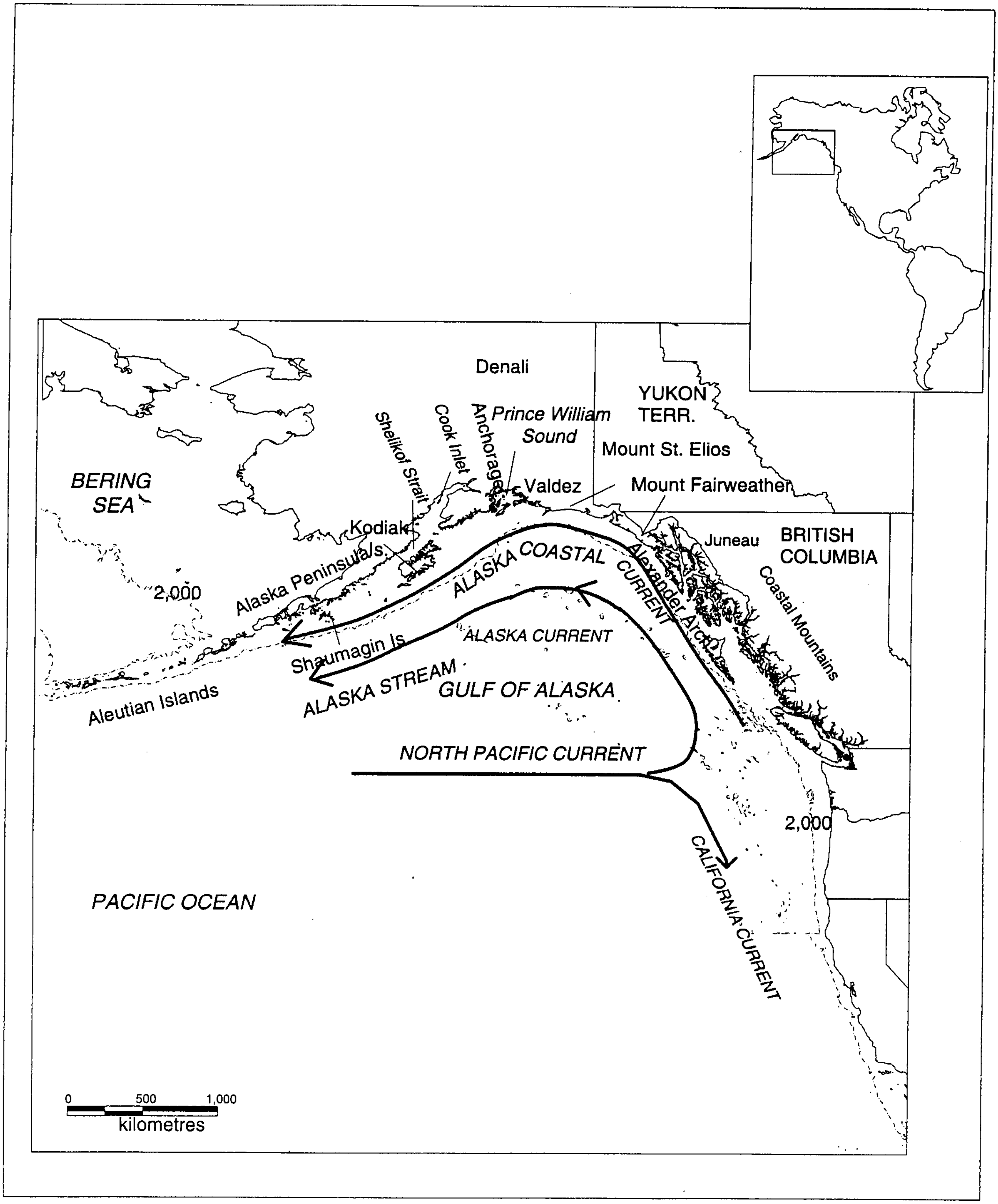

Fig 1. Map of Gulf of Alaska.

THE DEFINED REGION

The Gulf of Alaska (GOA) is defined as that area north of 52°N, between about 127°30'W on the east where it meets the British Columbia coast, and 176°W on the west including most of the Aleutian Islands. The GOA includes very rugged and extreme coasts with Cook Inlet in the north, Prince William Sound (PWS) just east of that, and Alexander Archipelago further southeast (Fig. 1). The western GOA includes the Alaska Peninsula coastline and the Shumagin and Kodiak Island groups. The arc formed between the extremes extends about 3600 kilometres. The GOA's continental shelf is estimated to be 336,000 km^2.

GEOGRAPHIC SETTING

The eastern and northern terrestrial margins of the GOA sustain very high natural erosion rates. The region is still undergoing de-glaciation from the last ice age, and contains the largest ice fields and glaciers in North America. The region also experiences rapid uplift from isostatic rebound following loss of ice field mass, and from continental uplift resulting from subduction of the northward-moving north Pacific plate. These processes have produced high mountain ranges immediately adjacent to the coast, with numerous short but high-volume and often high-velocity coastal streams and rivers that transport large sediment burdens to the GOA, especially where coastal glaciers are involved.

The mountains, many exceeding 2000 m, peak with Denali. As storms track across the GOA, the moisture-laden clouds are forced into this ring of mountains, which can produce localized annual rainfall exceeding 8 m per year or many times that amount in snow at the upper elevations. The GOA storms have no place to go as they pound against the mountains in what has been referred to as the graveyard of the North Pacific storms.

THE MAJOR SHALLOW WATER MARINE AND COASTAL HABITATS

The GOA shelf supports a diverse ecosystem that includes several commercially important fisheries such as crab, shrimp, pollock, salmon, and halibut. In aggregate these stocks imply that the GOA is amongst the world's largest fisheries with annual catches exceeding 300 g/1000 m^3 (Brodeur and Ware, 1992).

The relative dominance of the commercially important fish species changed in the mid-1970s; crab and shrimp declined while salmon and groundfish populations increased (see box). These population shifts coincided with the beginning of a decadal North Pacific change in the atmosphere and ocean. From the human perspective these alterations required the commercial fishing industry to invest substantially in infrastructure adjustments so as to remain economically viable. Subsequent changes in this ecosystem followed in the 1980s with substantial declines in populations of sea lions and puffins. Dramatic though this "regime shift" was, Parker et al. (1995) show evidence that the abundance of halibut and other commercially important species varies on decadal time scales in conjunction with northern North Pacific Ocean temperatures. These correlations and the regime shift suggest that the GOA ecosystem is sensitive to climate variations on time scales ranging from the interannual to the interdecadal; however, the specific mechanisms linking climate to ecosystem alterations are unknown. Elucidation of these mechanisms requires an understanding of the seasonal cycle of the principal physical, chemical and biological variables.

PHYSICAL OCEANOGRAPHY

The alongshore flow on the shelf and slope of the GOA is generally cyclonic (Reed and Schumacher, 1986). Flow over the continental slope consists of the Alaska Current, a relatively broad, diffuse flow in the north and northeast GOA, and the Alaskan Stream, a swift, narrow, western boundary current in the west and northwest GOA (Fig. 1). Together these currents comprise the poleward limb of the North Pacific Ocean's subarctic gyre and they provide the oceanic connection between the GOA shelf and the Pacific Ocean. Reed and Schumacher (1986) suggest that flow in the Alaskan Stream is relatively constant year round. However, Musgrave et al. (1992) and Okkonen (1992) show that sometimes the Alaskan Stream captures large eddies or forms prominent meanders and Royer (1982) suggests that the seasonal signal in baroclinic transport is less than 10% of the mean flow. In the northeast GOA, the "Sitka Eddy" occasionally forms and slowly propagates westward across the GOA. To the extent that these low-frequency features impinge on the shelfbreak they could contribute to the shelf circulation and exchange of water masses.

The most striking feature of the shelf circulation is the Alaska Coastal Current (Fig. 1), a swift (0.2–1.8 m s^{-1}), coastally constrained flow, typically found within 35 km of the coast. This current persists throughout the year and circumscribes the GOA shelf for at least some 2500 km from where it originates on the northern British Columbia shelf (or possibly even the Columbia River depending on the season) to where it enters the Bering Sea in the western GOA. In contrast to the coastal current, the shelf flow between the offshore edge of the coastal current and the shelfbreak is weaker and more variable. The source of this variability is uncertain, but potential mechanisms include separation of the coastal current as it flows around coastal promontories; baroclinic instability of the coastal jet or meandering of the Alaska Current along the shelfbreak.

The dynamics of the basin and the shelf are closely coupled to the Aleutian Low pressure system. Storm systems propagate eastward into the GOA and are then

Trophic Shift in Marine Communities in the Gulf of Alaska

Recently there has been information presented that the Gulf of Alaska (GOA) ecosystem has undergone some abrupt and significant environmentally induced changes starting in the mid to late 1970s (Piatt and Anderson, 1996; Anderson et al., 1997; Anderson and Piatt, 1999). Most of the biological changes in the NE Pacific and the GOA follow from the lowest trophic levels through the benthic and pelagic fish stocks to sea birds and marine mammals. The extent and degree of these changes are now well documented and provide an important perspective in determining future strategies for management of the marine ecosystem in the GOA. Environmental change has been indicated as the greatest influence on the system, and it is likely that changes in the environment will continue to occur in the future as they have in the past. Probably one of the best long-term data series that is useful in describing environmentally induced changes in the GOA is the data collected from small-mesh trawl surveys conducted nearly continuously from 1953 to the present. These data are used here to demonstrate the great degree of control that the environment has on the ecological structure of the GOA.

GOA OCEAN/CLIMATE VARIABILITY

Perhaps the broadest measure of contemporary climate variability in the GOA is the North Pacific Pressure Index (NPPI) which represents a wide-spread and relatively low frequency climate signal that has significant impact on the GOA ocean circulation and temperature (Fig. 1a). The NPPI models the changing location and intensity of the Aleutian low. Persistent strong blocking high pressure ridges during winter over eastern Asia (Siberian high) displace the Aleutian low to the south and intensify it (Wilson and Overland, 1986). This leads to cold northwest winds in the western and central

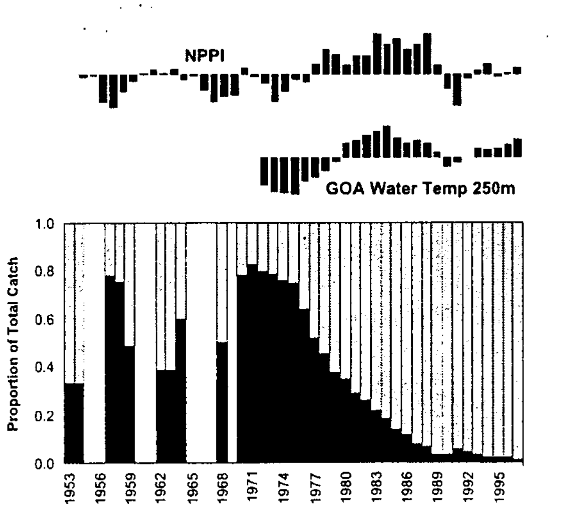

Fig. 1a. Normalised anomalies of North Pacific pressure Index (NPPI) and Gulf of Alaska water temperature at 250 m compared with long term composition of small-mesh trawl survey catch composition (3-year running average) in the Gulf of Alaska from 1953 to 1997 (from Anderson and Piatt, 1999).

GOA which favour upwelling in nearshore areas along with rapid cooling of the water column. When the storm track follows a more northerly tack across the Pacific, the nearshore region of the GOA is more subject to vertical mixing and downwelling. These two semi-stable states generally typify the two climate regimes of the GOA, the first representing the cold regime and the latter the warm regime. Analysing dendroclimatic data, back to about 1500, it appears these two climate regimes have oscillated at an average frequency of 15 years with the longest warm period lasting 34 years and the longest cold period lasting 26 years (Ingraham et al., 1998). The current warm period should have reverted to the cold dominated regime in 1995 according to analysis by Ingraham et al. (1998). Wiles et al. (1998), found evidence of the ENSO effect in GOA coastal tree-ring chronologies as well as evidence for a bidecadal oscillation (19 years) in the climate tendency of the GOA region. It thus appears that the climate varies in the GOA in a somewhat predictable fashion with either the cold or warm regime lasting from one to three decades before reversal. Changes in the climatology of the NE Pacific and the GOA lead to changes in ocean conditions that have a direct effect on the marine ecosystem. Lower trophic level animals demonstrate a particularly rapid response to environmentally induced changes.

POPULATION CHANGES OF SHRIMP AND FORAGE FISH

Many shrimps and forage fish (mostly in the family Osmeridae) can be considered trophospecies; they share similar prey and predators. Shrimp and forage fish react very quickly to environmentally induced changes, owing to their low relative trophic level. These forage species groups declined from relatively high levels in abundance in the period 1970–1984 to uniformly low abundance across a broad region of the GOA after 1985 (Anderson et al., 1997). Capelin (*Mallotus villosus*) composed 84% of the osmerid biomass prior to 1981; recently the dominant species has shifted to Eulachon (*Thaleichthys pacificus*). A change in the composition and timing of zooplankton abundance that was observed in the GOA after the late 1970s (Mackas et al., 1998; Brodeur and Ware, 1992) could have adversely affected planktivores like shrimp and forage fish. These changes highlight some of the major changes in abundance and population structure that have recently been observed in the GOA after the climate change that occurred in 1977 (Fig. 1b).

MAJOR INCREASES IN COD AND GROUNDFISH

In stark contrast to the decline of crustacean and forage fish populations have been the increase of Pacific cod, walleye pollock, and several species of pleuronectid groundfish. Yearly CPUE of arrowtooth flounder (*Atheresthes stomias*) exhibited a pattern opposite to that of the pink shrimp, increasing from a low of 0.02 kg/km in 1971 to a high of 28.8 kg/km in 1992. Arrowtooth flounder were caught in inshore bays near Kodiak Island during 1985–1995 where they were not present before. Mean CPUE of arrowtooth flounder increased in virtually every bay sampled. Areas of greatest increase in mean CPUE (up to 410.7 kg/km per grid cell) were east and north of Kodiak Island, and east of Afognak Island at Portlock Bank. Lesser increases were seen in bays west and south of Kodiak Island, and bays east of the Alaska Peninsula. Yearly CPUE of walleye pollock increased from a low of 17.5 kg/km in 1975 to a high of 284.8 kg/km in 1991. The greatest increase in mean CPUE (up to 410.7 kg/km) occurred in bays southeast of Kodiak Island and Portlock Bank. Lesser increases occurred in bays east of the Alaska Peninsula, south of Kodiak Island and southeast of Afognak Island.

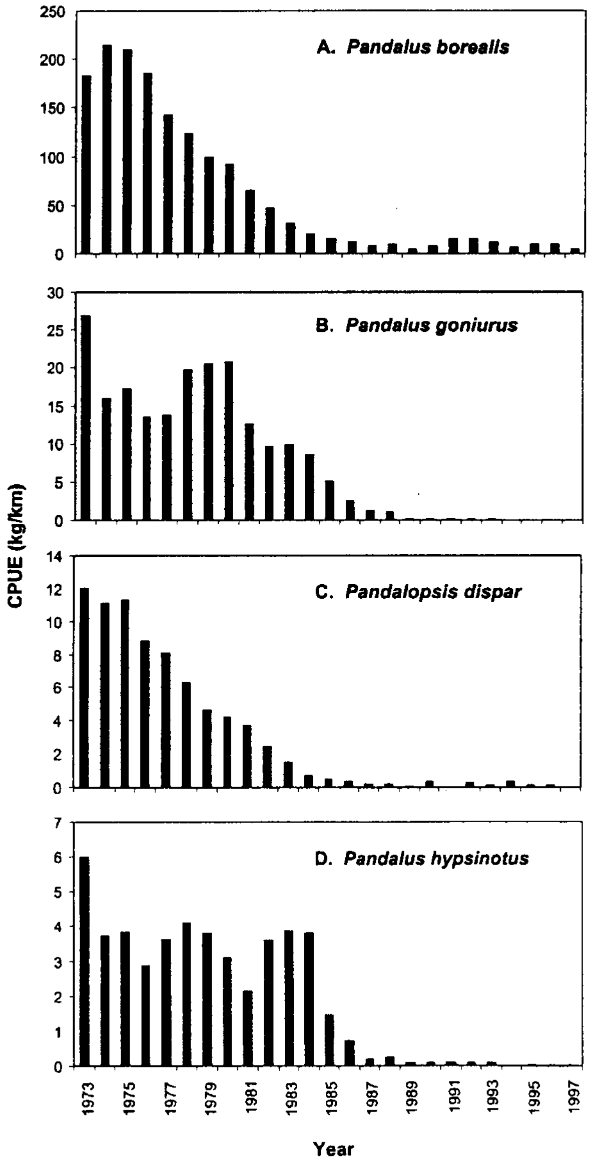

Fig. 1b. Relative abundance of (a) *Pandalus borealis*, (b) *P. goniurus*, (c) *Pandalopsis dispar* and (d) *Pandalus hypsinotus* in the Gulf of Alaska 1973–1997 (data smoothed 3-year running average).

CONCLUSION

As indicated by abrupt changes in NPPI, and sea temperature at depth (250 m) anomalies (Fig. 1a), average climate in the GOA shifted from cool to warm around 1977 (Mantua et al., 1997). Standardized trawl data collected from 1953 to 1997 reveal the ecological impact of this climate regime shift. Most of the increasing taxa are benthic or demersal in the adult stage (cod, pollock, flatfish, starfish), some are pelagic (jellyfish, cephalopods), and while most decreasing taxa are generally pelagic as adults, some are benthic (crab, sculpin). Although there were historically large fisheries for pandalid shrimp in many areas of the GOA (Orensanz et al., 1998), they also declined in areas that were seldom, if ever, fished (Anderson and Gaffney, 1977) and populations continued to decline even after fisheries were eliminated. Capelin have never been targeted by commercial fisheries in the GOA. Simultaneous declines were also noted in ecologically disparate taxa such as crabs, sculpins, herring, pricklebacks, eelpouts, snailfish, greenling, sablefish and Atka mackerel.The geographic and temporal coherence of the collapse of so many taxa argues for a large-scale common cause such as climate change, a conclusion also reached by Orensanz et al. (1998). The strength of association between shrimp catches and water temperature supports the hypothesis that the GOA ecosystem is regulated to a large degree by "bottom-up" processes (Francis et al., 1998, McGowan et al., 1998).

Decadal fluctuations in biomass and composition of fish communities apparently had a direct impact on sea birds and marine mammals that subsist on forage species and juvenile age groups of groundfish (Francis et al., 1998). During the cold regime prior to 1977, seabirds and marine mammals relied on fatty forage species such as capelin. As forage biomass declined in the early 1980s, forage species disappeared from bird and mammal diets and were replaced largely by juvenile pollock (Piatt and Anderson, 1996; Merrick et al., 1997). Declines in production and abundance of several sea bird and marine mammal populations in the GOA followed (Piatt and Anderson, 1996). Because juvenile pollock have low energy densities compared to fatty forage species such as capelin (Payne et al., 1999), some predator declines may be attributable to changes in diet composition. Perhaps more importantly, the total biomass of all forage taxa, including juvenile pollock, may now be limiting owing to the enormous food demands of adult groundfish. (Livingston, 1993; Yang, 1993; Hollowed et al., 1999). Marine mammal populations are, in general, thought to be food-limited (Estes, 1979). Population changes of marine mammals in the GOA most likely reflect the changed composition and abundance of preferred food sources. Climate-induced changes in the entire ecosystem from the lowest to the highest levels occur at different temporal scales, abrupt and rapid population change occurs at the low trophic levels while higher trophic levels are constrained by a mixture of "top-down" and "bottom-up" processes which take more time to manifest themselves.

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blocked by the mountain ranges of Alaska and British Columbia. Thus the regional winds are strong and cyclonic and the precipitation rates are very high. The positive wind-stress curl forces cyclonic circulation in the deep GOA while on the shelf these winds impel an onshore surface Ekman drift and establish a cross-shore pressure gradient that forces the Alaska Coastal Current. The high rates of precipitation cause an enormous freshwater flux (~20% larger than the average Mississippi River discharge) that feeds the shelf as a "coastal line source" extending from Southeast Alaska to Kodiak Island (Royer, 1982). The seasonal variability in winds and freshwater discharge is large. The mean monthly "upwelling index" at locations on the GOA shelf is negative in most months indicating the prevalence of coastal convergence (e.g., this index is a measure of the strength of cyclonic wind stress in the GOA). Cyclonic winds are strongest from November through March and feeble or even weakly anticyclonic in summer when the Aleutian Low is displaced by the North Pacific High (Wilson and Overland, 1986). The seasonal runoff cycle exhibits slightly different phasing from the winds; it is maximum in early fall, decreases rapidly through winter when precipitation is stored as snow, and attains a secondary maximum in spring due to snowmelt.

The shelf hydrography and circulation vary seasonally and are linked to the annual cycles of wind and freshwater discharge. The cross-shore salinity structure mimics density on the GOA shelf in April and September. In April, the stratification and the offshore front (defined here to be the surface intersection of the 32.0 isohaline) are relatively weak. By contrast in September, a 25 km wide wedge of strongly stratified water lies adjacent to the coast and is bounded on the offshore side by a prominent front. Royer et al. (1979) showed that surface drifters released on the shelf but shoreward of the front drifted onshore in accordance with Ekman dynamics. Upon encountering the front the drifters moved in the alongfront (e.g. westward) direction consistent with the geostrophic tendency implied by the cross-shore density distributions. Royer et al. (1979) hypothesized that ageostrophic offshore spreading of the dilute surface layer occurred on the inshore side of the front. In their analysis of currents measured inshore of the front, Johnson et al. (1988) found that this is indeed the case and that surface offshore flow was positively, and significantly, correlated with discharge. These studies imply that near-surface waters converge from either side of the front. This pattern of cross-shelf circulation would tend to accumulate plankton which might then attract foraging fish. Moreover, the front and the region inshore of it might be an area of enhanced productivity because entrainment and/or frontal instability could resupply the surface layer with nutrients from depth. The alongshore transport appears to be important in advecting zooplankton to important juvenile fish foraging areas.

Near-bottom salinities are higher in fall than spring. Xiong and Royer (1984) showed that on average maximum bottom salinities occur in fall and are nearly coincident with minimum surface salinities and maximum inshore stratification. Although the surface waters are diluted by coastal discharge (which peaks in fall), the source of the high salinity water is the onshore intrusion of slope water in response to the seasonal relaxation (or reversal) in downwelling.

Royer's (1996) analysis of monthly anomalies from the GOA shelf show very low-frequency (interdecadal) variations in bottom water salinity that imply interannual variability in the onshore flux of slope water and/or differences in slope water properties. These differences likely result in differences in the onshore flux of nutrients to the GOA shelf.

PRIMARY PRODUCTIVITY AND NUTRIENT CYCLES

There are few primary production measurements from this region and those that were made were done so at widely varying locations and times. However, satellite images of phytoplankton indicate the GOA to generate a relatively high level of primary production along the continental shelf (Fig. 2). While both Sambrotto and Lorenzen (1986) and Parsons (1986) conclude that the largest production rates occur on the shelf, nothing can be said about interannual variability. An additional limitation in understanding production here is the lack of nutrient data, particularly from the shelf. We do know that the shelf's nutrient source must be from the deep ocean as the coastal runoff nutrient concentrations are very low. These low concentrations are not unexpected given the steep, mountainous coastline and the extensive snow fields. Conceivably the shelf euphotic zone, especially in inshore waters, becomes nutrient-depleted but we emphasize that this is not known.

Fig. 2. Free-floating photosynthetic organisms (phytoplankton). This figure shows the Gulf of Alaska waters to be highly productive. Upon closer inspection the waters in Lower Cook Inlet are exceptionally productive. Image from NASA.

Although little is known about surface nutrient concentrations, there are suggestions of large year-to-year differences in subsurface nutrient concentrations. Incze and Ainair (1996) show large interannual differences in nutrient concentrations at depths >150 m along one section in Shelikof Strait (in the western GOA) that they occupied each spring between 1985 and 1989. Because of the unique bathymetry of this area it is unclear whether these differences apply to other GOA shelf regions. We speculate that the interannual salinity variations shown by Royer (1996) imply variability in deep water nutrient concentrations. These nutrient data are the only synoptic deep ocean and shelf nutrient data available for the northern GOA. The salinity–NO_3 relationship is correlated using data from between 125 and 450 m depth at stations within the Alaskan Stream and on the western shelf. This depth interval covers the range of bottom water salinities observed by Royer (1996) and Xiong and Royer (1984). The correlation appears to be good and we note that a change in salinity from 32.0 to 33.0 involves nearly a doubling in the NO_3 concentrations.

Zooplankton

Zooplankton are a critical link in the transfer of energy from primary producers to apex predators. Therefore, any process influencing the abundance and distribution of zooplankton can ultimately have an impact on fisheries. Zooplankton are therefore a critical component of attempts to understand the relationship of long-term climate variations to fish production.

The zooplankton community on the shelf of the GOA is dominated by a combination of oceanic and neritic herbivorous and omnivorous copepod stocks (Cooney, 1986a,b; Incze et al., 1996). The major oceanic species include *Neocalanus plumchrus, N. flemingeri, N. cristatus, Eucalanus bungii* and *Metridia pacifica*. Neritic taxa are dominated by *Pseudocalanus* spp. and *Calanus marshallae*, with lesser amounts of *Acartia* spp., *Centropages abdominalis* and *Calanus pacificus*. In addition to copepods, a number of micronektonic species contribute substantially to the overall density of forage for fish on the GOA shelf. The euphausiid species include primarily *Thysanoessa inermis, T. spinifera* and *Euphausia pacifica*, with lower densities of *Thysanoessa raschii, T. longipes, T. inspinata, Tessarabrachion oculatum* and *Euphausia pacifica*. Amphipods include *Cyphocaris challengeri, Parathemisto pacifica*, and *Primno macropa*. Oceanographic conditions affecting the transport and production of these taxa influence their absolute and relative densities and distribution over the shelf, and thus their availability to fish predators on the shelf.

During spring and summer, 25–78% of the copepod biomass over the shelf is dominated by the oceanic species complex. The distribution of oceanic relative to neritic copepods is determined to a large extent by cross-shelf transport (Cooney, 1986a) and water mass type (Incze et al., 1996; Napp et al., 1996). Although most of the copepod biomass in lower Shelikof Strait occurred consistently in the Alaska Coastal Current from 1986–1989; there was a four-fold (3–12 g C m^{-2}) interannual variation in maximum biomass (Incze et al., 1996; Napp et al., 1996). Zooplankton biomass on the shelf outside of Prince William Sound in May 1996 varied by up to an order of magnitude, with maximum values occurring in the shelf water offshore of the Alaska Coastal Current.

In addition to late copepodid stages of the major copepod taxa, the early naupliar stages are the primary forage for the first-feeding larval stages of a variety of fish. Based on water temperature, copepod development rates and flow rates of the Alaska Coastal Current, copepods producing the major cohort of naupliar stage larvae available to first-feeding pollock larvae in Shelikof Strait, originated during February–March on the shelf off Prince William Sound and east of GAK1 (GAK1 is a long-term oceanographic monitoring station just outside Resurrection Bay, Alaska). The nauplii consumed by first-feeding fish larvae are produced primarily by the neritic zooplankton community. Therefore, pre-bloom conditions on the north central GOA shelf might crucially influence survival of larval fish further downstream (west and south) near Kodiak Island.

No data are available on interannual differences in zooplankton biomass for the north central GOA shelf. However, a multi-year data set of zooplankton settled volumes measured during April and May near Ester Island, in the southern end of Prince William Sound, is available. In this part of Prince William Sound the zooplankton community is influenced primarily by advection from the GOA shelf. Cooney (pers. comm.) found a significant positive correlation between the logarithm of the average settled (zooplankton) volume for April and May and the average of the upwelling index on the northern GOA. The mechanistic link between these two variables is not obvious, or necessarily direct, as there are a number of possible explanations. In April and May oceanic species of the genus *Neocalanus* dominate zooplankton biomass suggesting a direct link that anomalously weak springtime downwelling enhances subsurface onshore transport of oceanic copepods from the shelfbreak. Alternatively, these same conditions could have elevated primary production (e.g., through onshore nutrient advection) during the spring months, thereby providing a more continuous and abundant zooplankton food supply. An anomalously positive April–May upwelling index implies reduced wind stress, precipitation rates, cloud cover and (perhaps) higher air temperatures. All these variables influence upper ocean stratification through wind mixing, surface heat flux and coastal discharge (note that cloud cover and air temperatures affect the springtime melt of snow accumulated through winter in the coastal mountain ranges). Stratification influences the vertical distribution of plant cells and, along with cloud cover (light availability), influences primary production rates. These physical variables through their influence on phytoplankton food quality and/or abundance would affect zooplankton.

If cross-shelf advection is a major source of zooplankton biomass on the shelf, then conditions that enhance zooplankton biomass at the shelfbreak should also enhance shelf zooplankton densities when favourable onshore transport conditions occur. Comparisons of zooplankton densities in the GOA between 1956–1962 and 1980–1989 show a doubling in average biomass around the GOA's perimeter since the early 1960s. The reason for this increase is uncertain, however, suggested hypotheses include increased primary productivity due to an increased winter wind stress and elevated summer winds producing a more northward displacement of the subarctic current into the GOA during the 1980s. The positive correlation between zooplankton densities and surface salinities suggests stronger vertical mixing (Brodeur and Ware, 1992) that led to enhanced new production and better feeding conditions for herbivorous zooplankton. Primary production rates were apparently three to four times higher in the GOA in 1987–1988 than earlier measurements indicated (Welschmeyer et al., 1993). Although the latter attribute the differences to methodology, the zooplankton and wind data cited above suggest that there might have been real decadal variation in annual production rates. Salmon probably benefited from these elevated zooplankton densities because salmon production nearly doubled between the 1950s and 1980s (Rogers, 1986). The major environmental shift suggested by the collapse of the crustacean fishery and its replacement by a ground fish fishery in the late 1970s and early 1980s could also be a consequence of enhanced zooplankton biomass because the early life history stages of demersal fishes feed on zooplankton.

Offshore Systems

The pelagic GOA is relatively productive biologically. The counterclockwise circulation at the margins produces continuous upwelling in the central GOA from Ekman pumping (Broecker, 1991), resulting in the continuous introduction of deep-water nutrients. This sustains year-round primary productivity that is modulated but still significant during winter, at an annual production rate as high as 170 g C m^{-2} y^{-1} (Welschmeyer et al., 1993). This comparatively high production concurrent with high nutrients (especially nitrate) and characteristically absent phytoplankton blooms (Parsons and Lalli, 1988) has been explained in part by micronutrient limitation by iron (Martin et al., 1991). In this scenario, low iron availability favours small phytoplankton cell sizes grazed continuously by both micro- and macrozooplankton (Miller, 1993). The doubling of zooplankton biomass, approximately doubled from the late 1950s to the 1980s, has led to coastal invasion by pelagic species, quite possibly in response to the climatically driven shift in the production regime during the mid-1970s (Brodeur and Ware, 1992).

HUMAN POPULATIONS AFFECTING THE AREA

About 500,000 people live in the terrestrial catchment basin draining into the GOA. More than half live in or near Anchorage in upper Cook Inlet, and nearly all of the remainder live in one of a dozen much smaller towns located along some 3000 km of coastline from Prince Rupert in the east to Kodiak in the west. Recent population growth has been slow, with a mean annual growth rate of less than 1% over the last 15 years. Previous population growth was more rapid, increasing from about 50,000 to 320,000 during the interval 1940 to 1980. The great majority of the significant human impacts in the region have occurred since 1940.

By far the most important primary industries in the region are related to natural resource extraction, followed by tourism. Manufacturing is negligible. Extraction-related industries include commercial fishing, logging, oil production and trans-shipment, and mining. Commercial fishing has been important since the late 19th century. Large-scale commercial logging of the coastal rainforest began in the 1950s and reached peak production in the 1980s, but has declined somewhat following closure of the two pulp mills in the region. Small-scale oil production occurred at Katalla during the first two decades of this century. Significant oil production began in Cook Inlet in the 1960s, and oil trans-shipments increased dramatically with the opening of the trans-Alaska pipeline terminal in 1977 at Valdez. Similarly, only two large-scale mining complexes have operated in the region: at Juneau (gold), and at McCarthy (copper), with ore from the latter exported as a concentrate. Another ore shipping terminal is located at Skagway for lead–zinc mines (currently closed) in the Yukon. Apart from these, other coastal mines have been scattered, small-scale operations, few of which currently operate.

BASELINE STUDIES—POLLUTANTS

The GOA is a candidate region for monitoring planet-wide dispersion of pollutants. Upwelling of deep oceanic water in the central GOA by Ekman pumping tends to divert surface waters away from the region, thereby exporting pollutants entrained in surface waters. The relatively small surface area of the terrestrial catchment basin provides few compartments for accumulation of pollutants before they are flushed into the Gulf by the heavy rainfall characteristic of the region, so terrestrial residence times are usually brief. The high erosion rates result in rapid burial of pollutants exported to coastal benthic sediments. Finally, the relatively sparse population concentrated in a few centres dispersed across a very long coastline, and the general absence of manufacturing, make local inputs negligible beyond the immediate vicinity of urbanization. Hence, pollution indicators that appear consistently at sampling sites remote from urbanized areas are *prima facie* evidence of long-distance pollutant transport and dispersion over a very large area.

Four baseline studies have been done to document pollutant levels or monitor trends. The earliest began in 1977 in Prince William Sound to document petroleum hydrocarbons in intertidal sediments and mussels prior to anticipated oil pollution along the marine oil-transport corridor through the PWS. This multi-seasonal study stopped in 1980 (Karinen et al., 1993), but resumed in 1989 just prior to beaching of oil spilled by the T/V *Exxon Valdez* (see box). The U.S. National Ocean Service, National Status and Trends (NS&T) program began monitoring intertidal sediments and mussels, and some benthic fishes in the region beginning in 1984 (in O'Connor and Pearce, 1999). Monitored analytes include polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCBs), DDT isomers, other chlorinated pesticides (listed in Brown et al., 1999, and Wade et al., 1999), butyltins and metals. Tributyltin concentrations were documented in mussels in 1987 (Short and Sharp, 1989). Finally, Regional Citizen's Advisory Councils (RCACs), which are federally-mandated but industry-funded semi-public oversight organizations, have commenced PAH monitoring in 1993 of marine sediments and mussels in Prince William Sound (Payne et al., 1998), and in Cook Inlet (Lees et al., 1999).

Results from these baseline studies indicate that the GOA is among the least polluted marine ecosystems on Earth. At sampling stations more than 10 to 20 km away from the outskirts of towns, pollutants are either near analytical detection limits, or else are geographically widespread within a low and relatively narrow concentration range. Pollutants in the first category include butyltins (Short and Sharp, 1989) and some of the less persistent, more recently introduced chlorinated pesticides (NS&T datasets). Pollutants in the second category include metals, PAHs and the persistent organic pollutants (POPs) such as PCBs, DDT-related compounds, and a few other chlorinated pesticides (Brown et al., 1999; Wade et al., 1999; NS&T datasets). PAHs in mussels are often not detected, and when detected are usually less than 20 ng/g dry weight at remote sites absent a clearly identifiable areawide pollution incident (such as the *Exxon Valdez* oil spill). A regional background of PAHs has been consistently detected in benthic sediments west of Yakutat Bay to Shelikof Strait, and has been attributed to oil seeps (Bence et al., 1996) but is more likely coal particles eroded from the extensive coastal deposits in the region (Short et al., 1999).

The consistent appearance of relatively narrow concentration ranges of POPs in sediments and mussels throughout the GOA coastline strongly suggests widespread dispersion in the upper water column. Concentrations of individual POPs in these matrixes are usually less than 1–2 ng/g. Benthic sediment core samples from the western GOA indicate accumulations of PCBs and DDTs beginning in the 1930s, and the other chlorinated organics one to two decades later (Iwata et al., 1994). These pollutants concentrate in higher trophic levels of the GOA food chain including the largely zooplanktivorous sockeye salmon (Ewald et

The *Exxon Valdez* Oil Spill

The *Exxon Valdez* oil spill (EVOS) is easily the single most devastating pollution event in the GOA to date. On March 24, 1989 the T/V *Exxon Valdez* struck Bligh Reef in Prince William Sound (PWS). At least 40,800 m^3 of crude oil, and possibly as much as three times that amount* spilled into PWS on the northern margin of the GOA. The spilled oil spread as a surface slick during the following three days, and was then mixed thoroughly with the seasurface layer by a high-energy storm over the next four days. Winds and currents carried the oil in a southwesterly direction over the next eight weeks, oiling shorelines intermittently along some 1750 km of coast extending up to 750 km from Bligh Reef. By the end of April 1989, about 40% of the spilled oil accumulated on beaches, 33% had dispersed into the water column, 20% evaporated, and the remainder was recovered, according to estimates based on the minimum spill volume (Wolfe et al., 1994). Ultimately, about 14% of the oil spilled was recovered.

The spill occurred at the worst time possible within the annual biological production cycle. The spring phytoplankton bloom typically begins in late March, with primary production near 300 g C/m^2/y over an extensive area within and outside PWS. This productivity supports a diverse food web, with a suite of apex predators attracted to the region to forage in support of further migrations or to reproduce. Avian and marine mammal predators that congregate in the area and associate with the sea surface were thus most affected. Even ten years after the EVOS there is continued evidence of cytochrome P450 elevation in intertidally dependent apex predators within the spill zone. This is strong evidence to suggest continued long-term exposure to *Exxon Valdez* oil via the intertidal food web to higher trophic levels, including sea otters and some sea ducks.

The effects of the EVOS on fish were less severe but at least as protracted as on marine mammals and birds. The most immediate effect on fish was through ingestion of oiled prey. The consequent poor growth especially of juveniles led to losses estimated at nearly 20% of the pink salmon year class (Geiger et al., 1996), which fortunately was largely mitigated by the hatcheries that had attained full-scale salmon production the same year. Nearly half the intertidal spawning habitat of Pacific herring was exposed to oil in PWS (Brown et al., 1996), which led to lower survival rates of larvae (Kocan et al., 1996). Oil that persisted in the intertidal over the next few years also caused longer term impacts to fish utilizing this habitat for reproduction. Both field and laboratory studies motivated by the EVOS found that fish embryos exposed to one part per billion concentrations of polycyclic aromatic hydrocarbons (PAH) exhibit a manifold of delayed effects that appear randomly among exposed populations throughout the life span duration (Carls et al., 1999; Heintz et al., 1999; Bue et al., 1998). Although these effects were not anticipated, population level impacts were small to negligible in the field, because of the limited persistence of the oil, the small proportion of available habitat affected and replenishment of affected populations by immigration.

Despite unprecedented efforts, attempts to clean the oiled beaches had very limited success. High-energy winter storms appeared to be at least as effective at re-introducing residual beach oil back into the water column, where it dispersed offshore into the Gulf of Alaska. By the end of 1992, beach cleaning efforts were terminated, and removal of the oil remaining was left to natural processes. Relatively unweathered oil was still present in 1998 in the interstices of cobble to boulder patches or beneath mussel beds on beaches that were heavily oiled initially (Irvine et al., 1999; Brodersen et al., 1999; Hayes and Michel, 1999; Babcock et al., 1996; Boehm et al., 1996). Oil in these remaining patches is substantially protected from further weathering or physical dispersion, and so is likely to persist on times scales of decades until dispersed by very high-energy storm events.

*The minimum release amount was provided by the spiller but was never independently verified, and the maximum corresponds with the capacity of the damaged cargo compartments. The actual amount spilled is likely somewhere between these extremes, because tidal and wave-driven oscillations of the impaled vessel probably replaced some of the oil with seawater in the hold.

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al., 1998), sea otters and Bald Eagles (Estes et al., 1997) and killer whales (Matkin et al., 1999). Adult sockeye salmon migrating to freshwater spawning grounds have recently been identified as the major vector transporting these pollutants to anadromous streams and lakes (Ewald et al., 1998). Likely proximate sources of these pollutants include wet and dry atmospheric deposition to surface waters of the GOA, and east Asian runoff carried to North America by the North Pacific current (Iwata et al., 1994; Ewald et al., 1998).

Concentrations of many of the monitored pollutants increase as urbanized areas are approached, but the NS&T data indicate that marine pollution at even the most polluted coastal stations monitored in the GOA is usually moderate compared with stations along the coast of the conterminous U.S. (NS&T datasets).

RURAL FACTORS

Agriculture in the GOA region is very limited and declining. However, agricultural practices in other parts of the world may contribute to contaminant loads found in the GOA food web. Industrial logging has involved widespread clear cutting on both public and private lands. This kind of logging can lead to severe habitat degradation for fish and wildlife, including reduction of salmon spawning and rearing habitat. The U.S. Department of Agriculture has, in recent years, reduced industrial logging on the national forests in Alaska. Logging on Native selected lands continues. The State of Alaska has adopted Forest Practices Act regulations that protect salmon streams. Salmon stream buffers and maintenance of large woody debris in streams and rivers are techniques useful for protecting and promoting healthy streams and salmon runs.

Fishing practices have the potential to impact the health of the GOA ecosystem. High seas gillnetting affected the population of target and non-target species in the GOA waters outside of State of Alaska jurisdiction. Fortunately, this type of fishing was prohibited. The dramatic increase in salmon sharks in the GOA waters may be in response to elimination of this fishing technique. Shark abundances in the GOA near shore (salmon sharks, and Pacific sleeper sharks) are much more abundant than 15 years ago. This, in itself, can result in dramatic restructuring of the GOA ecosystem.

Long-line fishing and bottom trawling can impact important fish habitat. Researchers are beginning to study essential fish habitats, as required under federal legislation, in hopes of defining and protecting this vital habitat. Long-line fishing techniques have been adjusted to protect endangered bird species. Some seabirds will take the bait as long-line gear is set, drowning the bird. Several avoidance techniques have been successful in reducing this non-intended take. Trawling exclusion zones have been employed to protect the endangered GOA Steller sea lion population.

EFFECTS FROM URBAN AND INDUSTRIAL ACTIVITIES

Industrial uses of the coast associated with timber harvest and the fishing industry include localized smothering of marine habitat due to log rafting and fish processing. When logs are rafted in the marine environment, the bark and debris can accumulate on the bottom altering the habitat, making it unsuitable to fish and crabs. Outfalls of fish processing facilities can result in hundreds of square metres being smothered in putrefying wastes. In both of these cases, State of Alaska resource managers are researching and addressing this issue using best management practices.

Tourism has become an important industry in Alaska. Large-scale cruise liners bring more than a million visitors annually. This increase in activities in the marine environment has led to increasing water and air pollution, and impacts to marine resources. As the tourism industry continues to grow, the likelihood of greater impacts will increase.

The GOA remains relatively unperturbed by anthropogenic pollutants, and its geographical situation together with the low human population density suggest that in future most of the pollution input will arise from distant sources, particularly east Asia. Prevailing patterns of wind flows and ocean currents tend to convey east Asia atmospheric pollution and terrestrial run-off to the GOA. Once there, replacement of surface water by pristine deep oceanic water upwelled within the central GOA tends to depurate these pollutants. Hence, increasing trends of pollution burdens in compartments of the GOA may signal parallel trends within large proportions of the entire North Pacific ocean. For these reasons, the GOA is an especially appropriate region for monitoring pollution trends of the North Pacific.

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